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# Head-free reading of horizontally and vertically arranged texts

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## Abstract

Parameters of eye and head movements and their coordination in reading horizontally and vertically arranged texts were compared. Reading was faster for horizontally arranged than for vertically arranged texts by 24%, primarily due to larger gaze amplitude for horizontal reading, and thus smaller numbers of saccades and fixations. The higher velocity of gaze saccades for given amplitudes in horizontal than vertical reading also contributed to the difference in reading speed. The horizontal bias in reading is at least partly due to the oculomotor system, because the higher velocity for given amplitude of horizontal saccade was also observed in a control experiment devoid of lexical load, in which a sequentially stepping laser target was tracked. The analysis of instantaneous phase of eye and head movements with a new metric derived by the Hilbert transform suggests that eye and head coupling is stronger for vertical than for horizontal direction in both reading and laser-tracking tasks. These results, combined with previous evidence that text familiarity modulates the timing and strength of head movement commands with respect to eye movements (Vis. Res. 39 (1999) 3761), indicate that the coupling strength between eye and head movements is variable depending on the direction of gaze shift and cognitive context. © 2002 Elsevier Science Ltd. All rights reserved.

**Keywords:** Human; Typography; Eye-head coordination; Gaze control; Phase coupling; Hilbert transform

## 1. Introduction

Studies examining the coordination between eye and head movements during visuomotor performance in simple or natural tasks have inspired a variety of ideas regarding the control signals of eye and head movements. Eye and head coordination during reading, scanning (Kowler et al., 1992), and driving (Land, 1992) have favored the idea that the eye and head motor systems receive a common command at almost the same time, and thus produce coupled movements, as summarized by the so-called *common gaze model* (Guitton, 1992). Based on electrical stimulation and single-unit recording in the primate superior colliculus, Freedman and Sparks (1997b) and Freedman, Stanford, and Sparks (1996) have presented the evidence on a neural substrate of the common command that a gaze displacement signal is coded within the motor map of the SC and subsequently decomposed into separate eye and

head displacement signals downstream from the colliculus. In contrast, Goossens and Van Opstal (1997) emphasized independent eye and head motor systems, based on the finding that during gaze control with eccentric initial eye positions, the head displacement vector was better related to initial target position with respect to the head (head motor error) than to initial target position with respect to the eye (gaze error). The common command model is also questioned by substantial inter- and intra-subject variability in head movement magnitude (Borel, Le Goff, Charade, & Berthoz, 1994; Fuller, 1992, 1996; Pelz, Hayhoe, & Loeber, 2001), occasional decoupling of eye and head movements during gaze saccades in response to double step targets (Ron & Berthoz, 1991), loosely coupled eye and head movement latencies (Tweed, Glenn, & Vilis, 1995), and context-dependent eye and head coordination during anticipatory pursuit (Collins & Barnes, 1999). A previous examination of eye and head movements in reading from this laboratory (Lee, 1999) showed that head movements were a primary target of cognitive control during reading, and suggested that text familiarity modulates the timing and strength of head movement command with respect to eye

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movements. It is possible that in addition to a pathway for a common gaze command responsible for coupled eye–head movements, there exists a separate head command pathway responsible for dynamic eye–head decoupling.

The apparent coupling of eye and head movements during reading is rather unexpected, because gaze saccades during reading are small, and it has been thought that head movements do not contribute to small gaze shifts (Freedman & Sparks, 1997a; Guitton & Volle, 1987; but see Kowler et al., 1992). However, in head-free reading where gaze saccades not only shift the line of sight, but also alter the starting position of the eye in the orbit for subsequent gaze saccades, coupling of head and eye movements has a role for keeping the eyes relatively central in the orbits. For the monkey, vertical gaze shifts, in comparison to horizontal shifts, are accompanied by little or virtually no head movements (Chen, Gandhi, & Sparks, 1999; Freedman & Sparks, 1997a). This is consistent with the idea that gaze trajectory follows the Fick–Gimbal model, in which a horizontal axis about which the eye rotates is nested within a fixed vertical axis about which the head rotates (Glenn & Vilis, 1992). The smaller head contribution for individual vertical gaze saccades suggested a differential coupling between eye and head movements, depending on reading direction.

In the current study, we quantitatively compared parameters of eye and head coordination in reading horizontally and vertically arranged Korean texts. The effects of orientation of typographic arrangement in English, Chinese, and Japanese have been studied in previous studies that primarily compared the efficiency of typography in terms of reading speed (Sun, Morita, & Stark, 1985; Tinker, 1955) and word recognition (Kajii & Osaka, 2000) between horizontal and vertical conditions. Here, we focus on differences in gaze parameters and the pattern of eye and head coordination between horizontal and vertical reading, as well as on the origin of those differences, which, even with their obvious practical significance, have never been directly addressed. One of our goals was to determine quantitatively the extent to which eye–head coordination differs between horizontal and vertical reading. In doing so, we applied a new metric obtained with the Hilbert transform, which has been successfully used to analyze synchronization between cardiac and respiratory rhythms (Schafer, Rosenblum, Kurths, & Abel, 1998). Another goal was to determine whether any differences are task-dependent, i.e. whether they are also present in a visual task devoid of lexical load, for which subjects follow a laser target sequentially stepped in horizontal and vertical directions, mimicking spatial and temporal patterns of gaze saccades during reading.

## 2. Methods

### 2.1. Subject and materials

Six college students participated in the experiment. They were 23–33 years old, and all were native Korean speakers, and had normal vision. They had no prior history of ocular motility disorder, and were not taking any medications. Three participants were experienced eye-tracking subjects. All subjects were naive with respect to the purpose of the experiment, and informed consent to participate was obtained.

Two texts written in Korean were selected from a college textbook that were judged comparable in difficulty. They both contained 76 words with an average of 3.3 syllables per word. Four reading materials were constructed by arranging each of these two texts in eight horizontal (left to right) or vertical (up to down) lines (Fig. 1). Horizontal and vertical versions of each text were made identical in font (Gothic), character size, aspect ratio of each character, number of characters in corresponding line, line spacing, and number of lines. The combinations of a horizontal arrangement of one text and a vertical arrangement of the other text constituted two experimental conditions to which six subjects were assigned, with the order of reading counter-balanced. The reading material was rear projected onto a tangent screen by an auto-focusing slide projector. The viewing distance was 114.6 cm, at which each syllable subtended  $0.95\text{--}1^\circ$ , and each horizontal or vertical line subtended  $51^\circ$ . The eight lines of reading material spanned  $17^\circ$ . The materials were presented in light green on a dark background for comfortable reading with reduced brightness and fatigue.

### 2.2. Recording eye and head movements

Horizontal and vertical positions of the eye and head were recorded with the search coil technique (Rommel, 1984, 1991; Robinson, 1963). For each subject, a two-dimensional induction coil embedded in a ring of silicone rubber (Skalar Medical, Netherlands) was placed around the cornea of the right eye after anesthetizing the conjunctiva with local anesthetic (0.5% proparacaine hydrochloride, Alcon). Subjects wore a cap on which another coil (38 mm in diameter, made of 10 turns of insulated copper wire) was firmly attached for detecting the direction of head orientation. The subject sat so that the head was placed at the center of a  $65\text{ cm} \times 65\text{ cm} \times 65\text{ cm}$  cubic frame that held two sets of coils in quadrature generating alternating magnetic fields at 50 and 75 kHz. Signals related to horizontal and vertical directions of the eye and head were filtered (a bandwidth of DC to 120 Hz), sampled at 500 Hz with a resolution

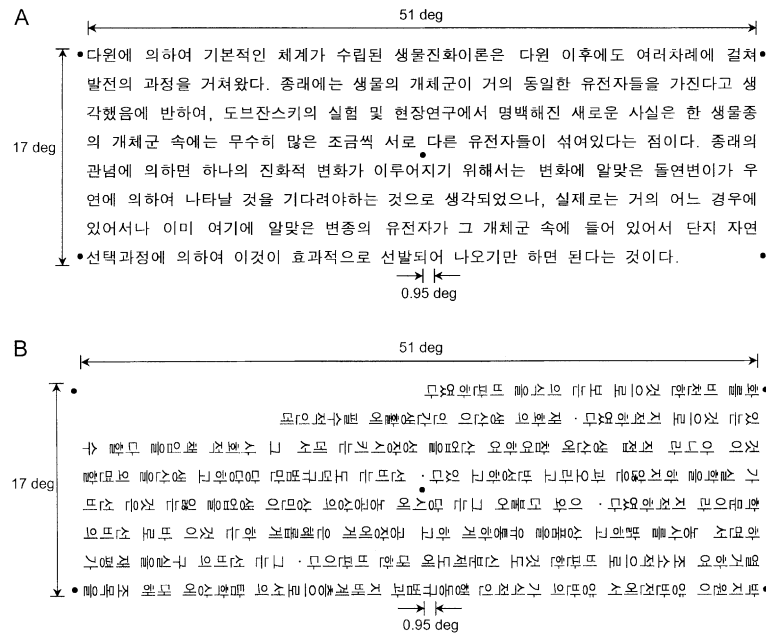


Fig. 1. Examples of texts for (A) horizontal and (B) vertical reading. The dimension of each text was  $51^\circ \times 17^\circ$ . In vertical texts, line progression is right to left. In written Korean, or *Hangul*, two to four letters from 10 vowels and 14 consonants are grouped into visually distinct characters representing syllables. Each character spanned  $0.95^\circ$ . Words are formed by one or more characters, and are separated by spaces. Five dots (four at each corner and one at the center of the text) were imbedded in the text for calibration purpose. The first seven lines contained 76 words both in horizontal and vertical texts and the data for the last (eighth) lines were excluded from analysis.

of 12 bits, and stored for off-line analysis. The peak-to-peak noise level at operating gain was approximately  $0.03^\circ$ , which corresponded to less than one A/D point.

Before the experimental session, the head coil was calibrated with a model head. For calibrating the eye coil, the offset value of the coil signal was set to zero while the coil was placed inside a metal pipe, which basically shielded it from all extrinsic signals (Straumann, Zee, Solomon, Lasker, & Roberts, 1995), and then the signal from the coil was mapped to a known angle. As a first approximation, rotational positions of the eye and head coils were obtained with a sinusoidal correction. Since the exact configuration of the eye coil when mounted onto the eye slightly varies, additional corrections were made off-line. These were based on average A/D values obtained while each subject maintained fixation on dots embedded along the spaces between lines of each text at fixed positions. The signal from the eye coil reflected gaze (i.e. combined eye and head movements), and thus, the eye positions in the orbit were derived by subtracting head positions (from the head coil) from gaze positions (from the eye coil). Details of this method and its potential errors are found elsewhere (Lee, 1999). Subjects were instructed to read the text naturally, without moving the torso.

### 2.3. Control experiment

In order to determine whether differences in the parameters of gaze saccades and in the pattern of eye-head coordination were due to inherent properties of the oculomotor system, we performed a control experiment, devoid of lexical load. A rear-projected laser target ( $0.2^\circ$  in diameter) was sequentially stepped a total of  $50^\circ$  in  $5^\circ$  increments either from left to right or from top to bottom by an XY scan head and its controller (DE series, General Scanning Inc., USA) interfaced with a host computer (IBM-PC586 compatible). The subjects were asked to track the target as accurately as possible. In order to maintain constant duration of target fixation, mimicking fairly constant fixation duration during reading, the target stepped 350 ms after gaze entered a  $2 \times 2^\circ$  electronic window centered about each target position. This period was empirically chosen to enable subjects to reliably follow sequential targets. Thus, the total dwell time for each target location was at least 400 ms (350 ms plus saccade latency). The mean fixation duration during reading, found to be approximately 240 ms, was too short to be used for this purpose. This difference supports the idea that during reading, sampling the text and programming of the upcoming saccade overlap in time during each fixation (e.g. McConkie, 1983). Such parallel processing would enable

earlier departures from each fixation by at least 160 ms. In contrast, for laser-tracking, visual acquisition of the target and programming a saccade occur sequentially, thereby delaying the departure from each fixation.

#### 2.4. Data analysis

The main parameters of interest were gaze amplitude, fixation duration, and the timing of head movements with respect to eye movements. During off-line analysis, periods that included blinking, return sweeps, and saccades of abnormal velocity characteristics were excluded. Gaze saccades were isolated with a velocity criterion of  $20^\circ \text{ s}^{-1}$ . The amplitude of gaze saccades, peak gaze velocity and fixation duration were measured and compared for horizontal and vertical reading (and laser tracking) conditions. In order to examine the timing of head movements with respect to eye movements, we first separated the ‘velocity pulse’ from the eye and head velocity signals. An *eye velocity pulse* was defined as the period of velocity signal related to an individual eye saccadic movement, the onset and offset of which were determined by a velocity criterion of  $20^\circ \text{ s}^{-1}$ . A *head velocity pulse* was determined by a pair of rising and falling segments of head velocity modulation, as defined by the zero-crossing of acceleration of head movement (for graphical presentation of this definition, see Fig. 4 of Lee (1999)). For each velocity pulse, the *velocity peak* was localized, and the interval between the eye and head velocity peaks for each gaze saccade was used as an index of eye–head coordination. Since head velocity pulses did not occur for every eye saccade, the head velocity pulse whose peak was temporally nearest to the eye velocity peak was used once and only once. When there was no head velocity peak during intersaccadic intervals before and after a gaze saccade, the gaze saccade was excluded from the analysis of this parameter.

In order to derive a quantitative index for frequency locking and the coupling strength of eye–head coordination during reading, we calculated instantaneous phase angle of eye and head signals using Hilbert transform (Cohen, 1995). The Hilbert transform,  $y(t)$ , of the given signal in time domain,  $x(t)$ , is defined by

$$y(t) = \mathbf{H}[x(t)] = (1/\pi) \int [x(t')/(t - t')] dt'. \quad (1)$$

Although natural signals are real, it is often advantageous to represent them as analytic signals in a complex form because the latter allow us to define the instantaneous attributes such as amplitude, phase and frequency. The real data,  $x(t)$ , and its Hilbert transform,  $y(t)$ , form the complex signal,  $z(t)$ , as

$$z(t) = x(t) + iy(t) = A(t) e^{i\varphi(t)}. \quad (2)$$

The instantaneous amplitude,  $A(t)$ , and instantaneous phase,  $\varphi(t)$ , (which, in nature, change in time) are given by,

$$A(t) = [x^2(t) + y^2(t)]^{1/2}, \quad (3)$$

and

$$\varphi(t) = \arctan[y(t)/x(t)]. \quad (4)$$

The real signal,  $x(t)$ , has a symmetrical density in frequency about the origin after Fourier transform. The spectrum of the complex signal,  $z(t)$ , is composed of the positive frequencies of the Fourier spectrum of  $x(t)$  only, and is zero for negative frequencies. The Hilbert transform has a property that all frequency components of the original signal have been phase-shifted by  $90^\circ$  without changing their amplitudes. For example, the Hilbert transform of a sine function is a cosine function. The Hilbert transform has been successfully applied to analyze synchronization between weakly coupled, irregular and non-stationary oscillators such as cardiac and respiratory rhythms (Schafer et al., 1998). The advantages of using the Hilbert transform for examining eye and head coupling are that their coupling and decoupling at each moment can be inferred at phase level even without apparent coupling at amplitude level, and thus it may constitute an ideal metric for describing eye and head coordination over an extended period. However, instantaneous phase relation is only a suggestive metric for coupling between eye and head movements.

The locked frequency between eye and head movements was compared between horizontal and vertical reading using the rate of change in instantaneous phase angle as an index for frequency locking. If eye and head movements are coupled, their phase plots against time will reveal yoked progressions. For this purpose, we derived phase information of eye and head velocity and acceleration with the Hilbert transform (MATLAB, Mathworks) for each line of text.

### 3. Results

#### 3.1. Amplitude of gaze and head movements and fixation duration

Fig. 2 illustrates the difference in gaze amplitude between horizontal and vertical reading. The amplitude of gaze saccades is larger in horizontal than in vertical reading for each subject (Fig. 2A) and for the overall population (Fig. 2B). The most frequently occurring amplitude also differed between the two conditions:  $4\text{--}6^\circ$  in horizontal and  $2\text{--}4^\circ$  in vertical reading (Fig. 2B). The mean gaze amplitude in the horizontal condition was  $4.6 (\pm 1.5)^\circ$ , and that for the vertical condition was  $3.6 (\pm 1.3)^\circ$ , the difference being significant ( $t_{(803)} = 10.23$ ,

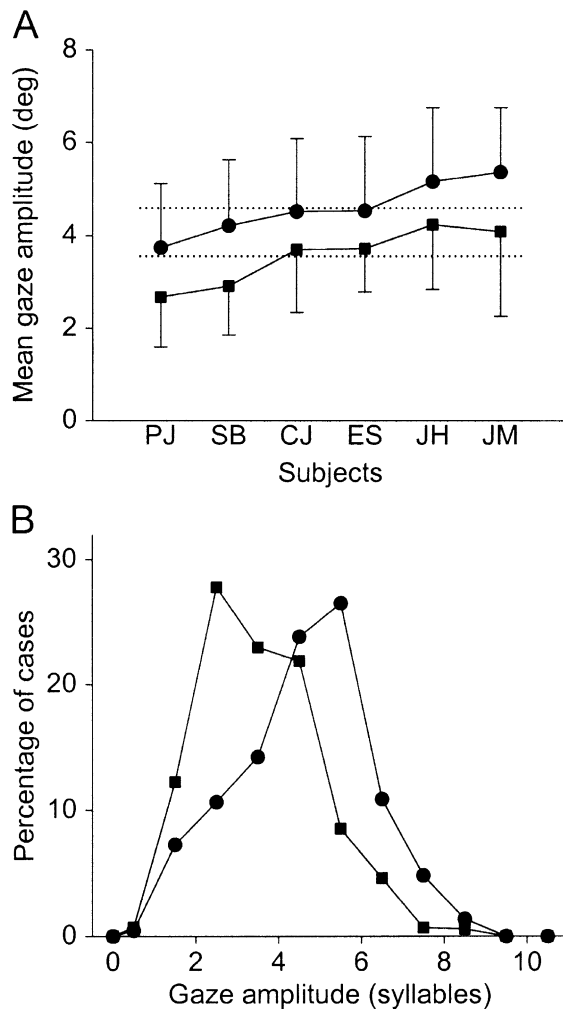


Fig. 2. (A) Gaze amplitude during horizontal and vertical reading for each subject, and (B) for overall population. A: Mean gaze amplitudes for each subject during horizontal (circles) and vertical (rectangles) reading are plotted in the order of their magnitudes, along with bars of one standard error. For horizontal reading, the amplitudes are  $3.7 (\pm 1.4)$ ,  $4.2 (\pm 1.4)$ ,  $4.5 (\pm 1.6)$ ,  $4.5 (\pm 1.6)$ ,  $5.2 (\pm 1.6)$ ,  $5.4 (\pm 1.4)^\circ$ ; for vertical reading,  $2.7 (\pm 1.1)$ ,  $2.9 (\pm 1.1)$ ,  $3.7 (\pm 1.4)$ ,  $3.7 (\pm 0.9)$ ,  $4.2 (\pm 1.4)$ ,  $4.1 (\pm 1.8)^\circ$ . B: Distribution of gaze amplitude during horizontal (circles) and vertical (rectangles) reading for all subjects. Means of the distributions are  $4.6 (\pm 1.5)^\circ$  for horizontal and  $3.6 (\pm 1.3)^\circ$  for vertical reading.

$p < 0.001$ ). However, the range of gaze amplitude was comparable in the two conditions.

The mean amplitude of head movement during gaze saccades was  $0.2 (\pm 0.2)^\circ$  in horizontal, and  $0.2 (\pm 0.2)^\circ$  in vertical reading conditions, with no statistically significant difference ( $p > 0.5$ ). Eye amplitude during gaze saccades was  $4.4 (\pm 1.5)^\circ$  in horizontal reading and was  $3.4 (\pm 1.3)^\circ$  in vertical reading, the difference being significant ( $t_{(803)} = 10.807$ ,  $p < 0.001$ ). These results indicate that the difference in gaze amplitude between horizontal and vertical reading was caused by the difference in the amplitude of eye saccades. The contribution of eye movements to gaze saccades was more than

Table 1  
Range of head movements

Subject	Head range ( $^\circ$ )	
	Horizontal	Vertical
PJ	10.77	7.52
SB	9.34	7.71
CJ	9.03	22.12
ES	17.57	19.82
JH	36.50	34.78
JM	3.21	11.49

Numbers are mean values obtained from seven lines. Note a high individual variation in head-movement tendency. JH was a “head mover”, and SB was a “non-head mover” (Fuller, 1992). CJ and JM showed larger head movement ranges for vertical than horizontal reading, whereas PJ and SB showed the opposite. Overall, there is no indication that the range of head position during horizontal reading is larger than that for vertical reading.

95% for horizontal and 94% for vertical conditions, with no significant difference between the two conditions.

The range of head position was similar for horizontal and vertical reading:  $14.40^\circ$  for horizontal and  $17.24^\circ$  for vertical conditions on average across all subjects (Table 1). This difference was not significant (paired  $t_{(5)} = 1.07$ ,  $p = 0.17$ ). The mean orbital position of the eye was also similar for horizontal and vertical reading:  $10.74 (\pm 3.55)^\circ$  for horizontal and  $11.26 (\pm 3.35)^\circ$  for vertical conditions on average across subjects ( $N = 42$ , 6 subjects  $\times$  7 lines). A test of equality of variance of orbital position showed that the difference in variance was not significant:  $6.59^\circ$  (mean variance of 42 lines,  $\pm 2.05^\circ$ ) for horizontal reading and  $6.89 (\pm 2.23)^\circ$  for vertical reading conditions.

In contrast to gaze amplitude, there was no statistically-significant difference in fixation duration between horizontal and vertical reading conditions ( $t_{(972)} = 1.58$ ,  $p > 0.1$ ). The distributions of fixation duration during horizontal and vertical reading matched closely, and the most frequent classes of fixation duration were the same in the two reading conditions (Fig. 3).

### 3.2. Peak velocity

The amplitude–velocity relationship, often called the *main sequence*, has been useful in describing metrical properties of saccadic eye movements. For given gaze amplitudes, the peak velocity of gaze saccades was higher for horizontal than vertical reading (Fig. 4). Since the number of saccades differed with gaze amplitude (more large-amplitude saccades in horizontal reading), we arbitrarily defined four-classes of saccade amplitude, from  $2^\circ$  to  $6^\circ$  in  $1^\circ$  steps, and tested the statistical significance of the mean difference in vectorial peak velocity for each amplitude class. The mean vectorial peak velocity of gaze saccades was higher in horizontal reading than that in vertical reading for all gaze

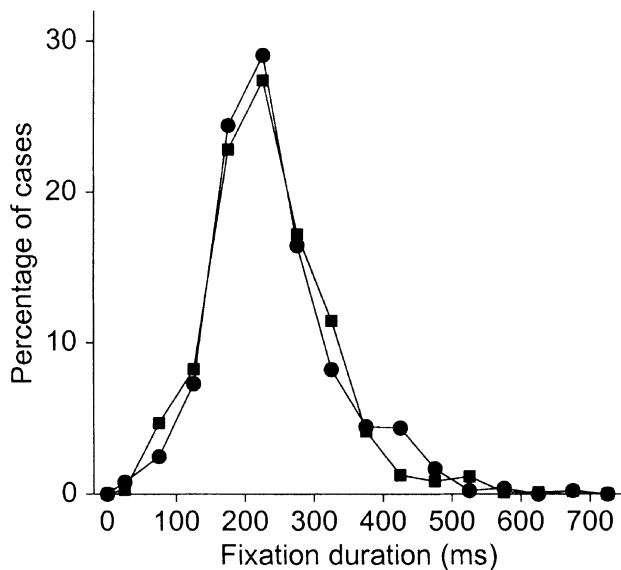


Fig. 3. Distributions of fixation duration during horizontal (circles) and vertical (rectangles) reading for all subjects. The means are 242 ms for horizontal and 233 ms vertical reading. Note a close similarity between the two distributions.

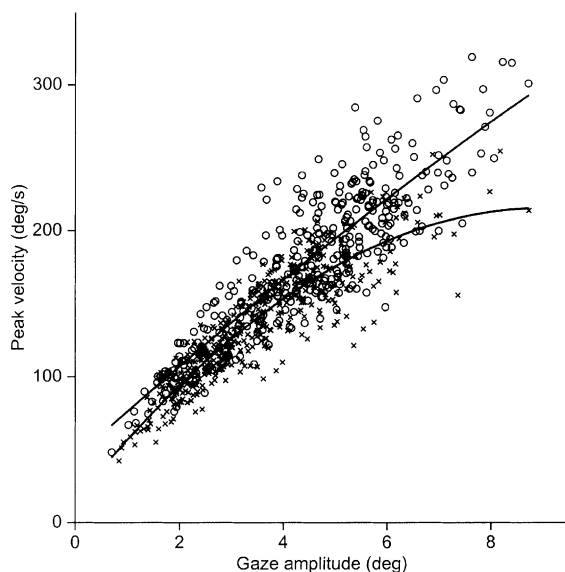


Fig. 4. Amplitude–velocity relationship for gaze saccades. Each symbol represents the peak vectorial velocity as a function of vectorial gaze amplitude during horizontal (circles) and vertical (crosses) reading. Data are fit with second-order polynomial functions using a least-square method: the upper curve for horizontal and the lower curve for vertical conditions. Mean peak velocity at any given amplitude is significantly higher for horizontal than for vertical reading (see text). In horizontal reading, the mean vectorial amplitude (combining both horizontal and vertical component amplitudes) is larger than horizontal component amplitude by only  $0.031^\circ$ , and in vertical reading, it is larger than vertical component amplitude by  $0.036^\circ$ . These values are negligible, indicating that the location of the texts were roughly centered about the primary position.

amplitude ( $t_{(176)} = 6.58$ ,  $p < 0.001$ ;  $t_{(159)} = 3.74$ ,  $p < 0.001$ ;  $t_{(167)} = 3.54$ ,  $p < 0.001$ ;  $t_{(120)} = 5.63$ ,  $p < 0.001$ ).

### 3.3. Coordination of eye and head movements

The coordination of eye and head movements was quantitatively examined with two different measures: occurrence of head-velocity pulse (see Section 2) in relation to eye-velocity pulse and synchronization between eye and head movements based on instantaneous phase angles. Analyses of these measures indicated that the coupling between eye and head movements was stronger for vertical than for horizontal reading conditions, as described below.

For most gaze saccades (83% in horizontal and 90% in vertical reading), the eye (gaze minus head) saccade was accompanied by a pulse of velocity change in the head movement within the preceding or following intersaccadic interval. For 74% of these gaze saccades in horizontal and 83% in vertical reading, the peaks of head velocity pulses followed or preceded the peaks of eye velocity pulses with time lags of less than 100 ms. Overall, the proportion of occurrence of velocity pulse within 100 ms interval for all gaze saccades was higher for vertical than for horizontal reading, and this difference was statistically significant ( $t_{(5)} = 2.38$ ,  $p = 0.03$ ). These results suggest that eye saccades are roughly coupled in time to head movements, and that the coupling appears to be tighter in vertical than horizontal reading (not because of smaller lag, but because of a higher coincidence). Fig. 5 shows histograms of the temporal lag between the peak velocities of associated eye and head movements for horizontal and vertical reading, compiled from all subjects. The mean time lags were 25.5 ms in horizontal, and 3.8 ms in vertical reading, indicating that in vertical reading, the peaks of eye- and head-velocity pulses occur almost simultaneously during gaze saccades. On the other hand, in horizontal reading, the peak of the head velocity pulse tends to follow that of the eye velocity pulse. This difference was statistically significant ( $t_{(612)} = 3.33$ ,  $p < 0.005$ ).

About 17% of total gaze saccades in horizontal and 10% in vertical reading were accompanied by no head-

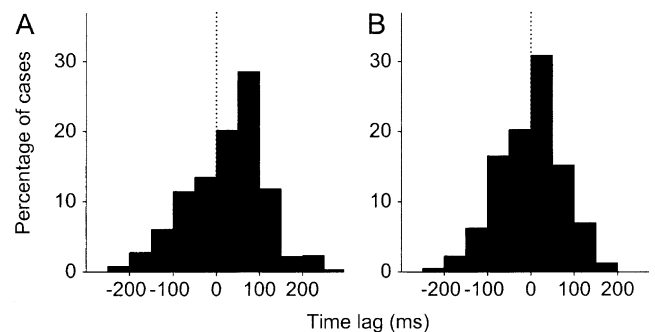


Fig. 5. Histograms of the temporal lag between peaks of eye and head velocities during gaze saccades in (A) horizontal and (B) vertical reading. Time lag is defined as time of head velocity peak minus time of eye velocity peak.

velocity pulses during intersaccadic intervals. This difference between horizontal and vertical conditions was observed in all subjects. For gaze saccades without head velocity pulses, the head moved at a relatively constant velocity, indicating that eye and head movements can decouple and that gaze saccades can be accomplished by different combinations of eye and head movements.

When each line of text was analyzed separately, we found a higher proportion of head velocity pulses in records from vertical than in horizontal reading. The mean differences between the numbers of eye saccades (eye velocity pulses) and head velocity pulses for each line of text, were 3.05 for horizontal and 1.07 for vertical reading ( $t = 3.28$ ,  $p < 0.01$ ), indicating fewer head velocity pulses per eye saccade for the horizontal condition.

Analysis of the instantaneous phase angles of the eye and head movements revealed the frequency-locked and unlocked portions within a single text line and this served as an indirect metric for dynamic change in strength of coupling between eye and head movements (Fig. 6). The plot of eye velocity in a phase plane (Fig. 6B) was relatively circular (i.e. symmetrical signal profile) and superimposed (i.e. regular signal amplitude). (For a pure sinusoid, perfectly superimposed Lissajous circles would result). However, the pattern of head velocity was irregular (Fig. 6A), and thus smaller modulations of head velocity (e.g. 0.5–1 s in Fig. 6A) made phase analysis (Fig. 6C) and comparison (Fig. 6D) difficult. Therefore, for the phase analysis, we used eye and head acceleration signals. The eye and head acceleration signals were derived (Fig. 6F), and their Hilbert transforms calculated. The phase progression of head acceleration was more regular (Fig. 6H) compared to that of head velocity (Fig. 6C). The instantaneous phase (unwrapped) of eye and head acceleration (Fig. 6I) was calculated with Eq. (4), and their difference (Fig. 6J) obtained. Unwrapped phase angles plotted against time (Fig. 6I) show phase progressions and provide information about dynamic phase synchronization. The similarity of slopes of the functions such as those shown in Fig. 6I (i.e. average frequency) for two oscillators is known to reflect their coupling strength (Rosenblum, Pikovsky, & Kurths, 1996). Two synchronous systems would show overlapped phase progressions, and thus, a constant phase difference. Eye and head movements shown in Fig. 6 show synchronization for the first second (near-zero phase difference in Fig. 6J for the first second). In order to determine whether the phase synchronization is correlated with gaze position, the instantaneous phase difference was examined for each line of text (as in Fig. 6J), and the occurrence of constant phase difference was not related to its time ( $x$ -axis of Fig. 6J, correlated to gaze position) in any apparent way.

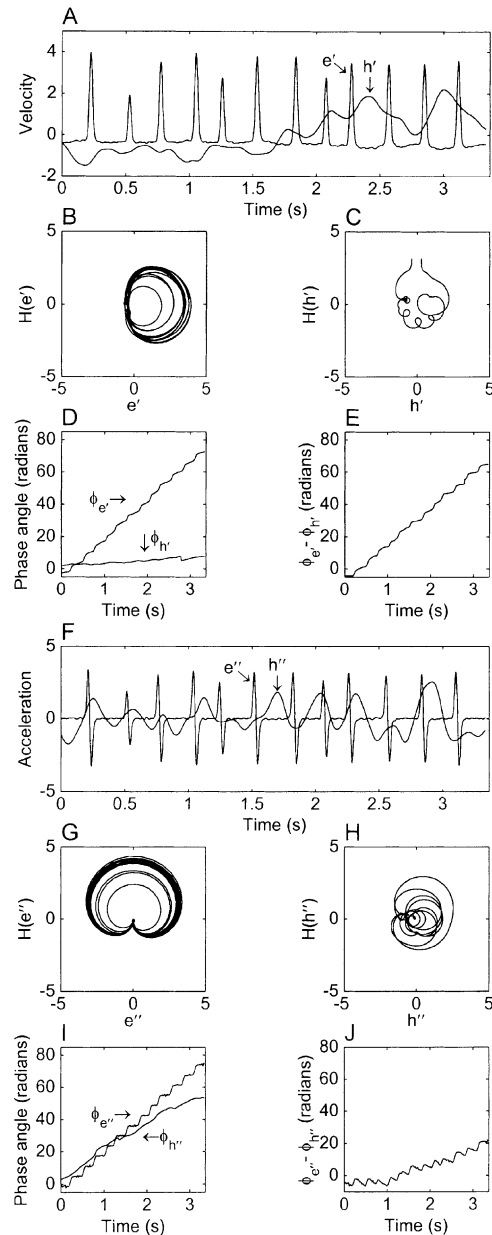


Fig. 6. Analysis of instantaneous phase of eye and head movements. (A) Normalized eye velocity ( $e'$ ) and head velocity ( $h'$ ) from a period during vertical reading of one complete line from a representative subject ES. (B) Plot of Hilbert transform of eye velocity,  $H(e')$ , vs eye velocity. (C) Plot of Hilbert transform of head velocity,  $H(h')$ , vs head velocity. This plot is much irregular compared to the plot of B, due to variable modulation of head velocity. (D) Unwrapped instantaneous phase of eye velocity ( $\phi_{e'}$ ) and head velocity ( $\phi_{h'}$ ). Phase  $\phi_{e'}$  is defined by  $\arctan(H(e')/e')$ , and  $\phi_{h'}$  by  $\arctan(H(h')/h')$ . (E) Instantaneous phase difference between eye and head velocities against time. (F) Normalized eye acceleration ( $e''$ ) and head acceleration ( $h''$ ). (G, H) Plots of Hilbert transform vs real data for eye and head acceleration. Note that head acceleration in (F) becomes much regular compared to head velocity in (A), and this is reflected as closer circles in (H). (I) Unwrapped instantaneous phases of eye acceleration ( $\phi_{e''}$ ) and head acceleration ( $\phi_{h''}$ ). Phase angle of eye acceleration stays the same during fixation and increases with saccades that form the dominant frequency of the eye acceleration signal. (J) Instantaneous phase difference between eye and head acceleration.

In order to quantify phase synchronization, we calculated the slopes of regression lines (average frequency) relating instantaneous phase angles of eye and head acceleration to time, as shown in Fig. 6I, for all lines of text. Fig. 7 shows frequency histograms of these slopes. For most cases, the slopes obtained from the phase signal of the eye were higher than those for the head, indicating that not all gaze saccades were accompanied by modulation of head velocity. The difference in the slope between the eye and head acceleration signals was larger in horizontal than in vertical reading ( $t_{(82)} = 2.47$ ,  $p = 0.007$ ). These results again suggest a weaker coupling between eye and head movements in horizontal reading, and a larger proportion of eye saccades without accompanying head-velocity pulses in horizontal than

vertical reading. Similar results were obtained from the analysis of phase synchronization between eye velocity and head acceleration ( $t_{(82)} = 3.797$ ,  $p < 0.001$ ).

### 3.4. Reading speed

Fig. 8 illustrates total reading times for horizontal and vertical reading, and factors contributing to them. Total reading time is the time taken to read the material as determined from the eye movement records. Because the number of words to be read was the same in both horizontal and vertical conditions, total reading time is a direct index of reading speed, and thus, potentially the efficiency of typography. Reading horizontally arranged text was, on average, 24% faster compared to reading

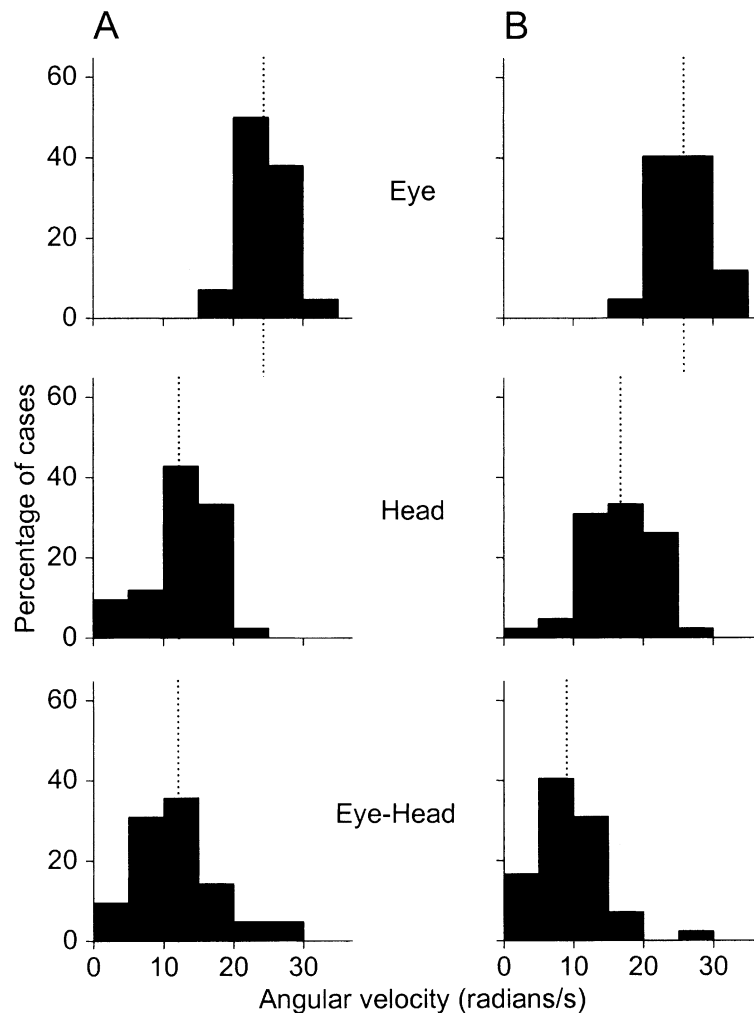


Fig. 7. Phase coupling between eye and head movements during (A) horizontal and (B) vertical reading. Shown are histograms of angular velocity (slopes of regression in Fig. 6I) of eye acceleration (upper panels) and head acceleration (middle panels) for each horizontal (A) and vertical (B) text lines. There are 42 cases for each histogram (one slope for each of seven lines of text for each of six subjects). Mean slopes of regression lines, indicated by dotted lines, for the eye and head acceleration signals were  $24.3 (\pm 3.4)$  and  $12.2 (\pm 4.6)$  in horizontal, and  $25.8 (\pm 4.4)$  and  $16.8 (\pm 4.8)$  for vertical reading, respectively. Lower two panels show histograms of the difference between angular velocities of eye and head acceleration. The mean differences (dotted lines) are  $12.1 (\pm 6.0)$  and  $9.0 (\pm 5.3)$  for horizontal and vertical conditions, respectively. The difference between the two conditions is statistically significant ( $t_{(82)} = 2.47$ ,  $p = 0.007$ ).



vertically arranged text. This difference could be explained by three factors: larger total durations of fixation, gaze, and regression periods for vertical reading (Fig. 8). The difference in total duration of fixation (fixations after forward gaze saccades) accounted for 70.2% of the total difference in reading time, whereas the total duration of forward gaze saccades and regressions (regressive saccades and fixations thereafter) accounted for only 13.4% and 16.4%, respectively. The longer (total) fixation for vertical reading was due to the larger number of saccades of smaller amplitude during vertical reading (mean duration of each fixation during horizontal and vertical reading was similar, as shown in Fig. 3). Total duration of gaze saccade is determined by the number, velocity and duration of gaze saccades. The mean durations of each gaze saccade in horizontal and vertical reading conditions were nearly identical. This was probably because larger gaze amplitude and higher gaze velocity in horizontal reading were compensated for by the smaller number of gaze saccades in horizontal reading, and vice versa.

### 3.5. Control experiment with point stimuli

In this experiment, the subjects were asked to track a laser target that sequentially stepped a total of  $50^\circ$  in  $5^\circ$  increments either from left to right or from top to bot-

tom. In this condition, saccade amplitude varied considerably (Fig. 9), even if the size of target step was fixed. The variability in saccade latency and thus the variable fixation duration (even with the fixed 350 ms duration after gaze entered an electronic window centered about each target locus) caused the timing of the target step irregular. Fixation of 350 ms was short and it was not an easy task to precisely land on targets, and subjects made several saccades including visually triggered, corrective, and self-generated predictive ones. We suspect that this caused the large variability in saccade amplitude and in peak velocity for given amplitude (Fig. 9). There was little difference in the overall range of gaze amplitude between horizontal and vertical tracking.

For four subjects out of six, the amplitude of gaze saccades toward laser targets sequentially stepped  $5^\circ$  from left to right was larger than for targets sequentially stepped from up to down. However, the overall difference in gaze amplitude between the horizontal and vertical tracking was smaller than that observed for horizontal and vertical reading, and was not significant ( $t_{(1039)} = 1.084$ ,  $p < 0.3$ ). It should be noted that in reading, gaze saccades are generated spontaneously, whereas in tracking a laser target, saccades are guided by a visual target. The difference in the amplitude–velocity relationship between horizontal and vertical tracking (Fig. 9) was comparable to that for horizontal and vertical reading (Fig. 4). The mean peak vectorial velocity was  $179.6^\circ$  and  $158.9^\circ \text{ s}^{-1}$  for horizontal and vertical tracking, respectively, and this difference was

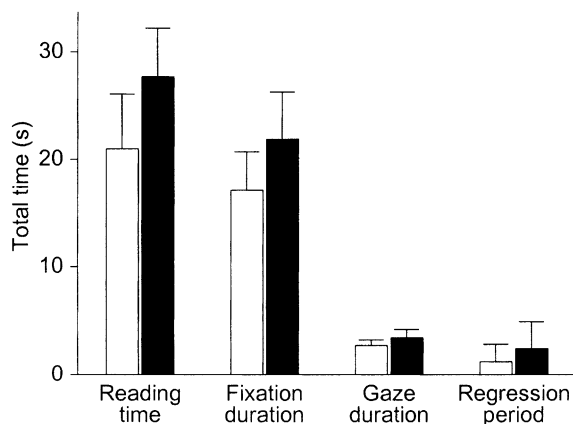


Fig. 8. Comparison of efficiency between horizontal and vertical reading. Plotted are difference in time taken to read horizontal and vertical reading (leftmost bars), and three factors influencing the difference: durations of fixation after forward gaze saccades, durations of forward gaze saccade, and durations of regressive saccade and fixation thereafter. Each bar indicates the mean of six subjects and a standard error of the mean for horizontal (open) and vertical (filled) reading. Note that 'fixation duration' is total duration of all forward fixations and that the longer fixation duration for vertical reading relative to horizontal reading reflects the larger number of saccades during vertical reading. The numbers of forward gaze saccade (and thus forward fixation) for horizontal and vertical reading were 77 and 110 (PJ), 61 and 86 (SB), 54 and 69 (CJ), 56 and 78 (ES), 53 and 67 (JH), and 44 and 50 (JM), respectively.

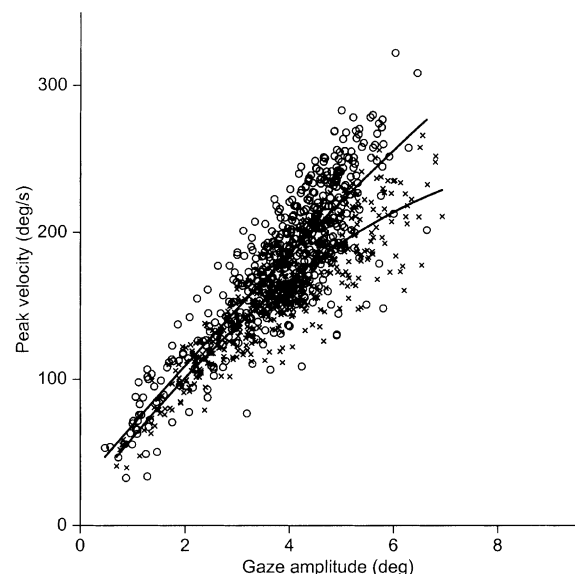


Fig. 9. Amplitude–velocity relationship for gaze saccades in laser-tracking task. Each symbol represents the peak vectorial velocity as function of vectorial gaze amplitude during horizontal (circles) and vertical (crosses) tracking. Data are fit with second-order polynomial functions using a least-square method: the upper curve for horizontal and the lower curve for vertical conditions.

statistically significant ( $t_{(1039)} = 6.74$ ,  $p < 0.001$ ). In both Figs. 4 and 9, the amplitude–velocity relationship showed a hint of a relatively earlier saturation of peak velocity in vertical conditions, as judged by least-square fit curves.

The peak vectorial velocity during reading was lower than that during laser tracking for gaze saccades of comparable size for both horizontal and vertical directions, as judged by scatter plots and least-square fit curves (not shown). For horizontal direction, the mean peak vectorial velocity of gaze saccades between  $3^\circ$  and  $5^\circ$  during reading was  $170.80 \pm 29.75^\circ \text{ s}^{-1}$  ( $N = 131$  out of 339 saccades, 38.64%), and that during laser tracking was  $188.76 \pm 33.55^\circ \text{ s}^{-1}$  ( $N = 350$  out of 503, 69.58%). This difference was statistically significant ( $t_{(479)} = 5.354$ ,  $p < 0.001$ ). Similarly, for vertical direction, the peak velocity during reading was  $153.65 \pm 22.49^\circ \text{ s}^{-1}$  ( $N = 199$  out of 450, 44.22%), and that during laser tracking was  $164.61 \pm 26.92^\circ \text{ s}^{-1}$  ( $N = 298$  out of 525, 56.76%). This difference was also significant ( $t_{(495)} = 4.742$ ,  $p < 0.001$ ).

The peak of the head-velocity pulse occurred most frequently within a 100 ms time interval before or after the peak of the eye-velocity pulse during tracking a laser target. The temporal lag between the peaks of eye- and head-velocity pulses was more variable for horizontal than vertical tracking, but the mean difference in temporal lag between horizontal and vertical tracking conditions was not statistically significant ( $t_{(696)} = 1.765$ ,  $p = 0.08$ ). In the control experiment, for more than 95% of gaze saccades, eye saccades were accompanied by a head velocity pulse. The analysis of instantaneous phase angles of eye and head signals revealed the same result as in the reading experiment regarding the coupling strength between eye and head movements. The mean differences between eye and head acceleration signals in the slopes of regression lines of phase angle as function of time (same parameters as shown in the bottom histograms of Fig. 7 for reading) were 3.88 rad/s for horizontal and 1.58 rad/s for vertical tracking conditions, and this difference was statistically significant ( $t_{(58)} = 2.48$ ,  $p = 0.008$ ), suggesting a weaker coupling between eye and head movements in horizontal tracking condition. The mean difference in the slope between eye velocity and head acceleration was also larger in horizontal than in vertical tracking ( $t_{(58)} = 3.34$ ,  $p < 0.002$ ).

## 4. Discussion

### 4.1. Stronger eye and head coupling in vertical direction

One main objective of the current study was to examine the direction of reading as a potential factor determining the strength of coupling between eye and head movements. Eye and head movements during vertical

reading were more strongly coupled than during horizontal reading: In vertical reading, eye and head velocity pulses concur more frequently, and the progression of head movements is more synchronized to the eye movements (Fig. 6).

The analysis method developed to analyze synchronization between weakly coupled, non-linear and irregular oscillators (Rosenblum et al., 1996; Schafer et al., 1998) reveals dynamic phase coupling. In the current study, this method was used to analyze the coupling strength between eye and head movements, and phase-locking between them (constant phase difference, or near-zero portions of Fig. 6J) was found to be dynamically determined. Vertical reading or tracking showed a smaller phase difference, and thus, a stronger coupling between eye and head movements than horizontal reading or tracking, as determined by comparing average frequency (phase angle divided by time) (Fig. 7). Since phase difference was dynamically determined, the coupling strength could be compared with combined periods showing absence of phase difference. Because the presence of phase difference does not necessarily mean absence of coupling between two oscillators (weakly coupled systems still show phase locking, see for an example, Fig. 1 of Rosenblum et al. (1996)), a comparison of angular velocity, as done in the current study, is more appropriate. A strong coupling correlates the amplitudes of two signals, but in the case of reading, the amplitudes of eye and head signals are generally uncorrelated (correlation coefficient with zero time lag in Fig. 6A is  $-0.12$  (and  $0.07$  in Fig. 6F), although occasional phase locking reveals a moderate correlation (the correlation during the first one second in Fig. 6A is  $-0.21$  (and  $-0.12$  in Fig. 6F)). Thus, phase-locking between eye and head movements without correlation of two signal amplitudes indicates a weak coupling between eye and head movements.

The stronger coupling between eye and head movements for vertical reading may seem contradictory to results obtained from the monkey indicating that vertical gaze shifts are accompanied by little or virtually no head movements (Chen et al., 1999; Freedman & Sparks, 1997a), and from the human indicating that the head contributes more to horizontal than to vertical gaze shifts (Glenn & Vilis, 1992; Tweed et al., 1995). However, it should be noted that single gaze saccades and reading are two different tasks. In single saccade tasks, each gaze saccade brings the line of sight from near the primary eye position toward visual targets presented at unexpected loci and times, and the line of sight resets back to the start position before the next saccade, whereas in reading, each gaze saccades shifts not only the line of sight, but the start position of the next saccade. Thus, in the current experimental condition where the text lines were  $51^\circ$  long, the range of head position during vertical reading (Table 1) was no smaller

than that for horizontal reading. Goossens & Van Opstal (1997) examined human eye and head coordination during gaze shifts toward visual or auditory targets presented in the two-dimensional frontal plane. They found that the gain for horizontal head displacements (horizontal head movement divided by the initial horizontal head motor error) was higher than the vertical gain, and yet the difference in the latency of onset for eye and head movements was smaller for vertical than for horizontal displacement components for both visual and auditory targets (Goossens & Van Opstal, 1997, Fig. 10), suggesting a more synchronized coupling in vertical than in horizontal dimensions. Thus, movement amplitude is not necessarily a major determinant of coupling strength between eye and head movements.

It is known that gaze holding and the accuracy of saccades deteriorate with increasing eccentricity (Becker & Klein, 1973; Stahl, 2001; Yao & Peck, 1997). However, the stronger coupling between eye and head movements during vertical reading is not likely due to lower tolerance for eccentric orbital positions in the vertical direction than in the horizontal direction, because the mean and variance of orbital position of the eye was similar for horizontal and vertical reading (see Section 3). Previous studies indicate that eye and head movement strategy depends on the task: for example, auditory-evoked gaze shifts are achieved with smaller eye–head latency difference and larger head movements than visually-evoked shifts (Goossens & Van Opstal, 1997), and eye and head coordination in reading is modulated by text familiarity (Lee, 1999). Consistent with this, Ceylan, Henriques, Tweed, & Crawford (2000) showed that depending on motor tasks, different motor strategies were adopted for head movement. They found that when head-free human subjects were instructed to shift their gaze between visual targets seen through pinhole goggles, the three-dimensional specification of head orientation switched from Fick-like range to a Listing-like range.

In the current study, the direction of reading and tracking was found to be one factor determining the strength of coupling between eye and head movements. It is now clear that the superior colliculus generates a signal of desired gaze displacement or gaze direction (Freedman & Sparks, 1997b; Klier, Wang, & Crawford, 2001). This signal is thought to be parceled out into separate signals for moving the eyes and head by downstream structures. The stronger coupling between eye and head movements during vertical reading and tracking suggests a variable efficiency in this parceling depending on the direction of gaze shift. However, it is also possible that other cortical areas may modulate the coupling strength by issuing independent eye (or head) control signals thereby adjusting the eye (or head) contribution or by adjusting the timing of head movements with respect to eye movement. Consistent with the lat-

ter, electrical stimulation of the primate frontal cortical areas results in a variable temporal relationship between eye and head movements; after electrical stimulation of sites in the frontal eye field, the head started to move after the stimulation-evoked eye (thus gaze) movement was completed, whereas stimulation of the supplementary eye field elicited both eye and head movements with the latter occurring first (Sparks, Freedman, Chen, & Gandhi, 2001). A previous examination of eye and head movements in reading from this laboratory (Lee, 1999) showed that head movements are a primary target of cognitive control during reading, and suggested that text familiarity modulates the timing and strength of head movement command with respect to eye movements. It is possible that in addition to a pathway for a common gaze command responsible for fixed coupling between eye and head movements, there exist other pathways responsible for dynamic eye–head decoupling.

#### 4.2. Comparison between horizontal and vertical reading

Languages are written in various directions, although this may seem strange to writers of English who are used to the left-to-right direction. *Hangul*, the written form of contemporary Korean language, like contemporary Chinese and Japanese written languages, are most often written horizontally from left to right, but sometimes vertically from top to bottom, and from right to left in rare occasions such as traditional calligraphy. Another objective of the current study was to quantify the difference in parameters of gaze shift between horizontal and vertical reading conditions, which has practical significance in evaluating the relative efficiency of horizontal and vertical typographies. Reading was faster for horizontally arranged than for vertically arranged texts, by 24% on average. The primary cause of this difference was smaller gaze amplitude for vertical reading, and thus more frequent saccade and fixation for a given length of text. Kajii & Osaka (2000) examined the recognition of briefly presented Japanese words, and found that the performance was better for horizontally displayed Japanese words than for vertically displayed words. It is likely that the smaller gaze amplitude for vertical reading is due to compensation for relatively poor recognition for vertical words. Weymouth, Hines, Acres, Raaf, & Wheeler (1928) showed a steeper decrease of visual acuity in the vertical than in the horizontal meridians. This shortcoming of acuity in the vertical meridian may reduce the number of characters that can be accurately recognized and thus the size of gaze amplitude in the vertical direction. The text lines tested in the current study were 51° long, longer than our typical reading material. The extent to which above bias of the visual system toward horizontal direction maintain the comparative efficiency of horizontal typography needs to be seen.

The contribution of eye movements to gaze saccades was similar for both horizontal and vertical reading conditions,  $\approx 95\%$ . The difference in gaze amplitude was mostly contributed by the eye saccades; the mean eye amplitude during horizontal gaze saccades was  $4.4 (\pm 1.5)^\circ$ , and was  $3.4 (\pm 1.3)^\circ$  for vertical saccades. The higher velocity for a given amplitude of gaze saccade in horizontal reading relative to vertical reading (Fig. 4) also contributed to the difference in reading speed. In contrast, head movements contributed little to the difference in reading speed. Because the higher velocity for given amplitude of horizontal saccade was also observed in a control experiment devoid of lexical load where a sequentially stepping laser target was tracked (Fig. 9), the higher velocity of saccades in horizontal reading probably reflects an intrinsic bias of the oculomotor system. Although the effect on gaze control of schooling that adopts primarily the horizontal typography needs yet to be systematically assessed, inherent differences between horizontal and vertical gaze shifts have been noted. Voluntary vertical saccades between two continuously visible targets are less accurate than horizontal saccades (Collewin, Erkelens, & Steinman, 1988a; Collewin, Erkelens, & Steinman, 1988b). The head makes predominantly horizontal movements whereas the eye makes vertical movements during oblique gaze shifts, and thus the gaze moves in Fick coordinates where the axis of eye rotation is nested within that of head rotation (Glenn & Vilis, 1992). Electrical stimulation at a few sites in the frontal cortex between the frontal eye field and supplementary eye field of rhesus monkey with the gaze pointing eccentrically and the head pointing straight ahead brought the direction of the head toward the current gaze direction (Sparks et al., 2001), and the magnitude of this head movement along the horizontal direction was larger than that along the vertical direction (their Fig. 9). There is cross-coupling between the vertical and torsional but not between the horizontal and torsional saccade generating systems (Lee, Zee, & Straumann, 2000).

There were no statistically significant differences in individual fixation duration between horizontal and vertical reading conditions. The duration and distribution pattern of individual fixations were very similar for horizontal and vertical reading (Fig. 3), suggesting that gaze amplitude and fixation duration are controlled independently, and that gaze amplitude is subject to the influence of visuomotor factors whereas fixation duration is not. These results are consonant with previous studies suggesting that the length of saccade and the duration of a fixation are independently made (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). The distributions of fixation duration obtained in our study were similar to those obtained for reading texts in English (Vitu, O'Regan, Inhoff, & Topolski, 1995).

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